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Industrial Gear Lubricants

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I. INTRODUCTION

The first operational gears consisted of wooden pegs set in a hub. Lubrication was thought not to be required, even though this system would have also benefited from it. Later the wooden pegs were replaced with metal gear teeth. Originally, animal fats were smeared on the gearing to reduce excessive wear and to minimize noise. During the Industrial Revolution many more demands were placed on gearing to transmit power reliably and to provide a relatively long service life for the equipment. Mineral oil gear lubricants were produced with newer additive packages that met these needs. Today the need for even higher productivity and greater efficiency in operation has placed severe demands on lubricants, demands that can no longer be met by mineral oil products in many applications. Synthetic gear oils were developed to meet these extreme demands.

Initially, it was the automotive industry that embraced synthetic lubricants as the solution to many automotive gearing problems. Both semisynthetics and fully synthetic automotive gear oils became popular in the 1960s through the 1970s. Industrial gear operators did not realize the benefits of synthetic lubricants until much later and are still in the process of acceptance. The American Gear Manufacturers Association (AGMA) lubricant specification that includes synthetic gear oils was not published until 1994.

Gears continue to be the most commonly used means of transmitting mechanical power and controlling motion. Because of this, gears are used in countless ways. Gears are manufactured in a wide variety of designs and sizes and operate under widely varying conditions and environments. The lubrication requirements are determined by these many variables [1]. To understand the development and application of synthetics in gear lubrication, it is necessary to review general principles of gears, gear lubrication, and how and why the technology developed. The following basic gear types are used to develop all gearing systems:

spur gears
helical gears
bevel gears
worm gears
hypoid gears.

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All these gearing systems can benefit to varying degrees from the use of synthetic gear lubricants. The systems are further described in Table 1 and Figs. 1–5 [2].

Gear systems may involve one or more of the basic gear designs. Their speeds can range from very low to very high while transmitting very light or heavy loads. The gearing systems may be enclosed in a gearbox or open to the elements. Speed, load, and the operating environment all have an effect on operating temperatures of a particular gearing system [3].

Lubricants for gearing systems have to perform the general task of transferring forces, minimizing wear, and reducing friction. If fluid lubricants are used, they also dissipate heat and remove abrasive particles. Depending on the type of gear and the operating conditions, gear lubricants have to meet various requirements. A universal gear lubricant does not exist that can meet all these requirements. Lubricant manufacturers have developed gear lubricants of different types (e.g., gear oils, gear greases, adhesive lubricants) with properties satisfying the individual operating needs.

Table 1 Basic Gear Types

Gear type	Description
Spur gears (Fig. 1)	Spur gears are characterized by their cylindrical shape and parallel shafts. The contact of the intermeshing teeth is linear over the entire flank width. Straight-toothed spur gears usually have one or two teeth in mesh at all times. Because of this, their load-carrying capacity is relatively low and they generate considerable noise.
Helical gears (Fig. 2)	Helical gears have parallel shafts like the spur gear system, but the tooth shape is either curved or helix, double helix or herring bone. Helical gears have a higher contact ratio, as well as lower shock loading and noise, since the flanks mesh gradually. Shaft bearing design is more complicated as a result of the axial forces that are generated. These axial thrust loads can be eliminated by means of double-helical or herringbone designs.
Bevel gears (Fig. 3)	Bevel gears are characterized by intersecting axes at 90° and a cone-shaped gear body. The gear teeth mesh in a line contact. Each tooth can be either straight like the spur gear or curved like the helical gear (a spiral bevel gear).
Worm gears (Fig. 4)	Worm gears consist of a worm, which resembles a screw, and a worm gear. These gears are characterized by shafts that cross at 90° and high transmission ratios (5:1 to 70:1 being common). Compared to the other gear systems, they have the best noise behavior, but their very high sliding forces result in frictional losses. Worm gears operate hotter and have lower efficiency than other gearing systems.
Hypoid gears (Fig. 5)	Hypoid gears are a form of spiral bevel gears. The axis of the pinion is below the axis of the ring gear. Therefore, this type of gearing has better load-carrying capacity than the standard bevel gear. Because of the increased contact ratio and additional sliding, hypoid gears operate much smoother than bevel gears.

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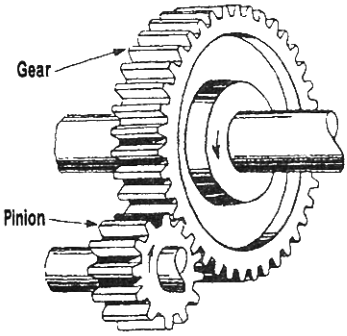

Figure 1 Spur gears.

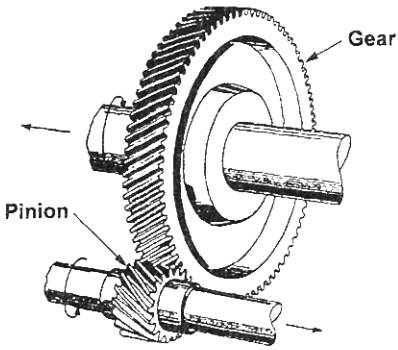

Figure 2 Helical gears.

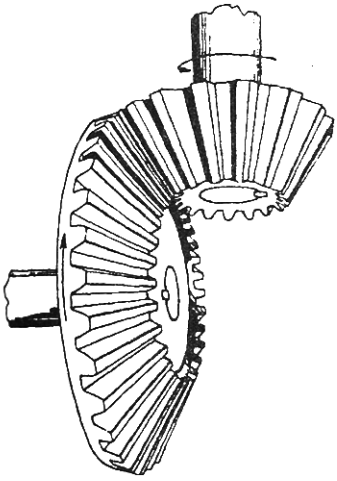

Figure 3 Straight tooth bevel gears.

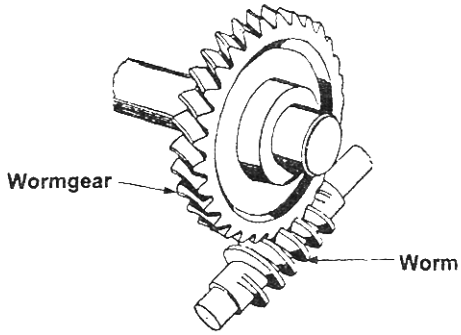

Figure 4 Worm gears.

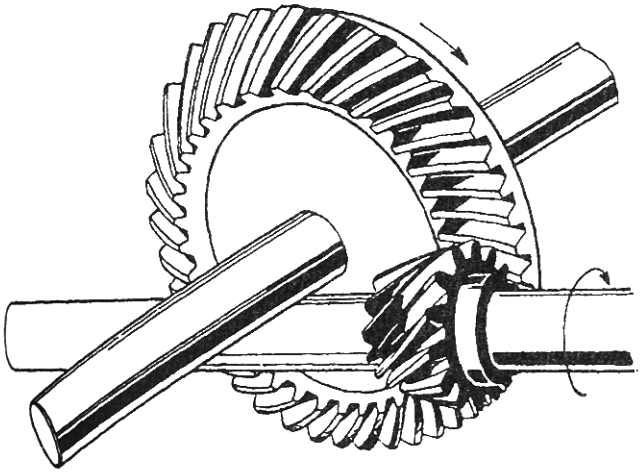

Figure 5 Hypoid gears.

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Gear oils have to meet the following requirements:

excellent resistance to aging and oxidation
low foaming tendency
good load-carrying capacity
neutrality toward the materials involved (ferrous and nonferrous metals, seals, paints)
suitability for high and/or low temperatures
good viscosity–temperature behavior

Gear greases, in contrast, are required to ensure the following:

good adhesion
low oil separation
low starting torques
compatibility with synthetic materials
noise dampening

Large open gear drives are lubricated with adhesive lubricants that must have:

excellent adhesion
optimum load-carrying and lubricating capacity under mixed friction conditions
good emergency running properties in case of starved lubrication
good pumping characteristics in automatic spraying equipment

Today's gear lubricants may also be required to meet special conditions. These conditions include regulations such as the regulations of the U.S. Department of Agriculture (USDA) that ensure safety of food products. These are the requirements identified by the USDA HI and H2 lubricant categories.

Governments and individuals are also becoming more aware of the impact of waste lubricants and lubricant contamination on the environment. New requirements for rapidly biodegradable gear lubricants are being identified now and will continue to be published in the future. Modern industries such as silicon chip and computer manufacturing are also placing new requirements on gear lubricants, calling for products that are functional in clean-room environments or in high vacuums. The need to reduce outgassing has placed special low vapor pressure requirements on modern lubricants.

II. HISTORICAL DEVELOPMENTS

A. Industrial Gear Oils

Lubrication specifications for industrial gear lubricants have historically been less formal than those for automotive lubricants [3]. Industrial gear systems consist of many different types and are used under a vast number of different conditions. Under normal operating conditions, severe demands are not placed on the lubricant in stationary applications. Currently as in the past, standards in North America for gear lubricants in industrial applications are written primarily by the AGMA. In Europe as well as in most of the rest of me world, industrial gear oil specifications are written by the Deutsches Institut für Normung (DIN). The requirements for open and enclosed gear systems established by the AGMA are listed in Tables 2–4. The requirements define tests for measurement of extreme pressure characteristics, oxidation protection, corrosion characteristics, water separation, and a variety of chemical and physical properties of the proposed lubricant. Most of the test procedures are defined by the American Society for Testing and Materials (ASTM). Until recently (1994), no dedicated specification existed for industrial

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Table 2 Minimum Physical and Performance Specification for Rust and Oxidation Inhibited Gear Lubricants, (Including Compounded Gear Lubricants)

Property	Test procedure	Criteria for acceptance
Viscosity	ISO 3104 ASTM D-445	Must be as specified by AGMA
Viscosity index	ISO 2909 ASTM D-2270	90 minimum
Oxidation stability	ISO 4263 ASTM D-943	Hours to reach a neutralization number of 2.0[a]

AGMA grade	Hours (minimum)
0, 1, 2	1500
3, 4	750
5, 6	500

Rust protection	ISO 7120 ASTM D-665B	No rust after 24 h with synthetic seawater	
Corrosion protection	ISO 2160 ASTM D-130	#1b corrosion class after 3 h at 121°C (250°F)	
Foam suppression	ASTM D-892	Must be within these limits:	

		Max volume of foam (mL) after	
	Temperature	5 min blow	10 min rest
Sequence I	24°C (75°F)	75	10
Sequence II	93.5°C (200°F)	75	10
Sequence III	24°C (75°F)	75	10

Demulsibility	ASTM D-2711	Must be within these limits:
	Water in the oil after 5 h test, max.	0.5%
	Cuff after centrifuging, max.	2.0 mL
	Total free water collected during entire test, min.	30.0 mL
Cleanliness	None	Must be free of visible suspended or settled contamination.

[a] The criteria for acceptance indicated for oxidation stability and demulsibility are not applicable to compounded gear oils.

Source: ANSI/AGMA 9005-D94.

gear lubricants formulated with synthetic fluids. The current AGMA specifications (Table 5) contain a category for synthetic lubricants.

Both the AGMA standards in North America and the DIN standards in Europe indicate only the minimum requirements for gear lubricants. Modern products, especially synthetic gear oils and greases, exceed these requirements. Similar to new technologies, new lubricant types are included in standards only if they have been used successfully for some time and have ed broad acceptance. State-of-the-art lubricant technology proves tfiat lubricants have kept pace with the general technological development and are well ahead of standardization. Table 6

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Table 3 Minimum Physical and Performance Specification for Extreme Pressure Gear Lubricants

Property	Test procedure	Criteria for acceptance
Viscosity	ISO 3104 ASTM D-445	Must be as specified by AGMA
Viscosity index	ISO 2909 ASTM D-2270	90 minimum (applies to viscosity grades 2 EP–8 EP only)
Oxidation stability	ASTM D-2893	Increase in kinematic viscosity of an oil sample at 121°C (250°F) should not exceed 6%[a]
Rust protection	ISO 7120 ASTM D-665B	No rust after 24 h with synthetic seawater[a]
Corrosion protection	ISO 2160 ASTM D-130	#1b corrosion class after 3 hours at 100°C (212°F)
Foam suppression	ASTM D-892	Must be within these limits:

		Max volume of foam (mL) after:	
	Temperature	5 min blow	10 min rest
Sequence I	24°C (75°F)	75	10
Sequence II	93.5°C (200°F)	75	10
Sequence III	24°C (75°F)	75	10

Demulsibility	ASTM D-2711 MOD	Must be within these limits[a]:		
			AGMA grades	
			2 EP–7 EP	8 EP–13 EP
		Max percent water in the oil after 5-h test	2.0%	2.0%
		Max cuff after centrifuging	1.0 mL	4.0 mL
		Min total free water collected during entire test (start with 90 mL of water)	80.0 mL	50.0 mL

Cleanliness	None	Must be free of visible suspended or settled contamination.
Load-carrying property	ASTM D-2782 (Timken test) and DIN 51 354 (FZG test)	An oil must meet both; a 60-pound Timken OK load and fail stage greater than 12 on the FZG machine with A/8.3/90°C parameters for acceptance.[a]
Filterability	None	Must be filterable to 25 μm (wet or dry) without loss of EP additive ($\beta 25 = 200$ filter rating)[b]

[a] Acceptance criteria have been upgraded.
[b] β number refers to filter efficiency. $\beta_{25} = 200$ means that for every 200 particles of 25 μm or larger, 1 particle will pass the filter.
Source: ANSI/AGMA 9005-D94.

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Table 4 Minimum Physical and Performance Specification for Synthetic Gear Lubricants

Property	Test procedure	Criteria for acceptance			
Viscosity	ISO 3104 ASTM D-455	Must be as specified by AGMA			
Viscosity index	ISO 2909 ASTM D-2270	120 minimum[a]			
Oxidation stability	ASTM D-2893	Increase in kinematic viscosity of oil sample at 121°C (250°F) should not exceed 6%			
Rust protection	ISO 7120 ASTM D-665B	No rust after 24 h with synthetic seawater			
Corrosion protection	ISO 2160 ASTM D-130	#1b corrosion class after 3 h at 121°C (250°F)			
Foam suppression	ASTM D-892	Must be within these limits:			
				Max volume of foam (mL) after	
			Temperature	5 min blow	10 min rest
		Sequence I	24°C (75°F)	75	10
		Sequence II	93.5°C (200°F)	75	10
		Sequence III	24°C (75°F)	75	10
Demulsibility	ASTM D-2711 MOD	Must be within these limits:[b]			
		Max percent water in the oil after 5 h test			1.0%
		Max cuff after centrifuging			2.0 mL
		Min total free water collected during entire test (start with 90 mL of water)			60.0 mL
Cleanliness	None	Must be free of visible suspended or settled contaminants			
Max, pour point	ISO 3016 ASTM D-97	−30°C (−22°F)			
Load-carrying property	DIN 51 354	An oil must meet 11 stage fail (10 stage pass) on FZG machine with A/8.3/90°C parameters for acceptance.			
Filterability	None	Must be filterable to 25 μm (wet or dry) without loss of additives (β25 = 200 filter rating)[c]			

[a] Esters having a lower viscosity index and meeting all other requirements of this specification may be used in specific applications where proper viscosity at operating temperature has been verified.
[b] Polyglycols which will not pass the demulsibility test, but meet all other requirements of this specification, may be used in specific applications where there is no danger of water contamination.
[c] See note in Table 3.
Source: ANSI/AGMA 9005-D94.

summarizes the current gear lubricant standards published by DIN. You will notice that the German standards still do not specifically list synthetic lubricants as a category.

B. Need for Synthetic Gear Lubricants

Synthetic gear lubricants are used whenever mineral gear lubricants have reached their performance limit and can no longer meet the requirements. These requirements include operation at very low or high temperatures, extremely high loads, and extraordinary ambient conditions.

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Table 5 Viscosity Ranges for AGMA Lubricants

Rust and oxidation inhibited gear oils: AGMA lubricant no.[a]	Viscosity range at 40°C (cSt)[b]	Equivalent ISO grade[b]	Extreme pressure gear lubricants AGMA lubricant no.[c]	Synthetic gear oils AGMA lubricant no.[d]
0	28.8–35.2	32		0 S
1	41.4–50.6	46		1 S
2	61.2–74.8	68	2 EP	2 S
3	90–110	100	3 EP	3 S
4	135–165	150	4 EP	4 S
5	198–242	220	5 EP	5 S
6	288–352	320	6 EP	6 S
7, 7 Comp	414–506	460	7 EP	7 S
8, 8 Comp	612–748	680	8 EP	8 S
8A Comp	900–1100	1000	8A EP	—
9	1350–1650	1500	9 EP	9 S
10	2880–3520	—	10 EP	10 S
11	4140–5060	—	11 EP	11 S
12	6120–7480	—	12 EP	12 S
	190–220 cSt at	—	—	—
13	100°C (212°F)[f]	—	13 EP	13 S

Residual compounds AGMA lubricant no.[e]	Viscosity ranges at 100°C (cSt)[f]
14R	428.5–857.0
15R	857.0–1714.0

[a] Oils marked Comp are compounded with 3–10% fatty or synthetic fatty oils.
[b] Per ISO 3448, *Industrial Liquid Lubricants—ISO Viscosity Classification*, Also ASTM D-2422 and British Standards Institution B.S. 4231.
[c] Extreme pressure lubricants should be used only when recommended by the gear manufacturer.
[d] Synthetic gear oils 9S–13S are available but not yet in wide use.
[e] Residual compounds–diluent type, commonly known as solvent cutbacks, are heavy oils containing a volatile, nonflammable diluent for ease of application. The diluent evaporates leaving a thick film of lubricant on the gear teeth. Viscosities listed are for the base compound without diluent.
[f] Viscosities of AGMA lubricant 13 and above are specified at 100°C (210°F), as measurement of viscosities of these heavy lubricants at 40°C (100°F) would not be practical.

CAUTION: Residual compounds may require special handling and storage procedures. Diluent can be toxic or irritating to the skin. Do not use these lubricants without proper ventilation. Consult lubricant supplier's instructions.
Source: ANSI/AGMA 9005-D94.

There may even be special requirements such as low flammability. Even though many properties of mineral oils can be improved by means of additives, it is not possible to exert unlimited influence on all their properties. This applies especially to properties that depend on the chemical structure of the lubricant, such as thermal resistance, low temperature behavior, flash point, and evaporation losses. Synthetic gear lubricants provide a number of advantages; however, they do not necessarily outperform mineral oils in all respects and may even result in some practical drawbacks despite their advantages.

The advantages of synthetic gear lubricants, depending on the base oil, are as follows:

improved thermal and oxidation resistance
improved viscosity–temperature behavior (higher viscosity index)

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Table 6 DIN Standard Requirements for Common Gear Lubricants

Standardized lubricants	Requirements	Type of lubricant	Application
CL lubricating oils	DIN 51517 Pt 2	Mineral oils with additives enhancing resistance to corrosion and aging	Gears subject to low loads, with a peripheral speed less than 30 m/s and a permanent oil bath temperature up to 100°C
CLP lubricating oils	DIN 51517 Pt 3	Mineral oils with additives enhancing resistance to corrosion and aging, and reducing wear under mixed friction conditions; FZG scuffing load stage (A/8.3/90): 12 min	Gears with high flank loads and/or a high sliding percentage; permanent oil bath temperature up to 100°C
L-TD lubricating and control oils	DIN 51515 Pt 1	Mineral oil base turbine oils with additives enhancing resistance to corrosion and aging	Gears in steam and gas turbines
HL hydraulic oils	DIN 51524 Pt 1	Pressure fluids made of mineral oils containing additives to enhance resistance against corrosion and aging	Combined application in hydraulic systems and gears
HLP hydraulic oils	DIN 51524 Pt 2	Pressure fluids made of mineral oils containing additives to enhance resistance against corrosion and aging and to reduce wear; FZG scuffing load stage (A/8.3/90): 10 min	Combined application in hydraulic systems and gears subject to a high degree of wear
Lubricating greases type G	DIN 51526	Fluid to very soft greases of NLGI grade 000 to 1, based on mineral and/or synthetic oil plus thickener	Splash lubrication of enclosed gears (e.g., gear motors, drum motors, actuators)

improved low temperature properties
lower evaporation losses
reduced flammability
improved lubricity
lower tendency to form residues
improved resistance to ambient media

Along with these advantages, there are possible disadvantages, which may include:

higher price
reaction in the presence of water (hydrolysis, corrosion)
Material compatibility problems (paints, elastomers, certain metals)
limited miscibility with mineral oils

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Application-related advantages usually prevail, however, with the result that synthetic lubricants will be increasingly used for gear lubrication, especially under critical operating conditions. As stated earlier, government regulations and OEM and end-user specifications will also increase the need for synthetic lubricants. The current mineral oil products used by the food processing industry that meet USDA HI requirements cannot perform to the same level as the new synthetic gear lubricants meeting the same food-grade requirements.

Also, the current vegetable-based products required for rapid biodegradability in marine application's and other outdoor environments cannot meet the same high demands as synthetic gear lubricants that are also rapidly biodegradable.

Both poly(α-olefin) (PAO) and ester oils are sometimes blended with a certain percentage of mineral oil to create a semisynthetic combination that provides several advantages. Semisynthetic gear oils can provide performance near that of a pure synthetic, but at a considerably lower price. This combination also increases the solubility of certain additives that are required for high performance. Also, the negative impact on nitrile butadiene rubber (NBR) seals can be reduced by adding a small amount of ester oil to a PAO gear oil. The blending of mineral oil and PAO oils is much more prevalent in automotive gear oil applications.

III. TYPES OF SYNTHETIC GEAR LUBRICANT

Synthetic gear lubricants based on PAOs, polyalkylene glycols (PAGs), and ester oils have proven particularly efficient in gearing systems.

A. Gear Lubricants Based on PAOs

PAOs are similar to mineral oil hydrocarbons in their chemical structure and are therefore also known as synthetic hydrocarbons. They are also similar to mineral oils with respect to compatibility with sealing materials, disposal, reprocessing, and miscibility with mineral oils. Their main advantages are their excellent low temperature behavior and oxidation stability. It is possible to manufacture food-grade lubricants (USDA-H1) for the food processing and the pharmaceutical industries with PAO base oils and special additives. Lower viscosity PAOs are also rapidly biodegradable.

B. Gear Lubricants Based on PAGs

Lubricants based on PAGs provide an especially low coefficient of friction, which makes them suitable for gears with a high sliding percentage. Specifically, these are worm and hypoid gears. If PAG oils contain the appropriate additives, they have an excellent antiwear effect on steel/bronze worm gear systems and a very good pressure absorption capacity. A negative impact on sealing materials and the solubility of some paints are some of the possible disadvantages. At operating temperatures above 100°C, only seals made of fluorinated rubber or polytetra fluoroethylene (PTFE) are resistant to PAGs. Below tfiis temperature, seals made of NBR are resistant to PAG lubricants. If the gearbox housings are to be coated on the interior with a paint system, it is recommended that epoxy or polyurethane resin paint systems be used. The miscibility of PAG with mineral oils is very limited, and mixtures should therefore be avoided. To ferrous metals and almost all nonferrous metals, PAG lubricants are neutral. If the gearing system has one gear made from aluminum or an aluminum alloy, there may be increased wear when there is a combination of high load and high sliding.

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C. Gear Lubricants Based on Ester Oils

Ester oils are the result of a reaction of acids and alcohols with water being separated. There are many different types of ester structure, and they all differ in their impacts on the chemical and physical properties of me lubricant. In the past, these lubricating oils were mainly used in aviation applications for the lubrication of aircraft engines and turbines, as well as gear systems and pumps, starters, and so on. Ester oils have a high thermal resistance and excellent low temperature behavior. Rapidly biodegradable ester oils will gain importance in industrial applications, since by selecting an appropriate ester-based oil, it is possible to achieve the same efficiency as with PAG gear lubricants.

IV. PERFORMANCE PROPERTIES

In general the advantages of synthetic gear lubricants are their thermal and oxidation stability, favorable viscosity–temperature behavior, high flash point, and good low temperature behavior. PAOs and PAGs also provide lower frictional losses in the gear train. Table 7 shows the average values of the most important properties of mineral oil compared to PAGs and PAOs [4].

A. Viscosity

Gear oils change their flow behavior depending on temperature and pressure. Their viscosity decreases with a rising temperature and increases with rising pressure. This crucial behavior of gear oils is, therefore, of primary importance when it is necessary to determine the required viscosity and to select a suitable type of oil for a particular application. The gear oil's viscosity has a significant impact on the gear lubrication function. Increased viscosity results in a thicker lubricant film, thus improving antiwear and damping behavior and to a certain extent the oil scuffing load capacity. If the viscosity is too high, increased churning and shearing losses result in excess heat, especially at an increased peripheral speed. If the viscosity is too low, mixed friction conditions will prevail and result in increased wear.

1. Viscosity–Temperature Behavior

All lubricating oils have a viscosity that varies inversely with temperature. Therefore, as temperature increases the viscosity of the oil decreases. The rate at which viscosity changes with temperature varies from oil to oil. An oil's viscosity–temperature behavior is generally depicted on special graph paper published by the ASTM. This graph paper is designed to display the

Table 7 Gear Oil Properties

Properties	Mineral oils	PAOs	Polyglycol oils
Density at 20°C, g/mL	0.9	0.85	0.9–1.1
Viscosity index	80–100	130–160	150–270
Pour point °C	−40 to −10	−50 to −30	−56 to −23
Flash point °C	<250	>200	150–300
Oxidation resistance	Moderate	Good	Good
Thermal stability	Moderate	Good	Good
Lubricity	Good	Good	Very good
Compatibility with elastomers, coatings, etc.	Good	Good	Insufficient to good
Price relation	1	5–10	6–10

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varying temperature–viscosity relationship of mineral oil as a straight line. Since a PAO is a synthetic hydrocarbon, it also is displayed as a straight line on this graph paper. Even though PAG oils are typically shown as straight lines on this graph paper, if more than two points were plotted for one oil, there would be a slight curve.

Figure 6 shows the different viscosity–temperature behaviors of a mineral oil, a PAO, and a PAG. Each of these products has an ISO viscosity grade of 460 or AGMA viscosity number of 7 [4]. The flatter the viscosity–temperature line, the less sensitive the viscosity to temperature change.

The viscosity index (VI) is used to describe the temperature-related change of viscosity. It is a dimensionless number, and a high viscosity index indicates a small change in viscosity relative to the temperature change. A low viscosity index number indicates a much greater sensitivity to temperature change. Table 7 shows the viscosity index range of several oils. In practice, a high viscosity index means that a gear system will start smoothly at low temperature conditions and have only minimal power losses. It can also mean that at increased temperatures, a load-bearing lubricant film is formed that provides good protection against wear. Synthetic gear oils clearly have a higher viscosity index than mineral gear oils.

2. Viscosity–Pressure Behavior

A lubricating oil's viscosity increases when the pressure rises. Elastohydrodynamic (EHD) action occurring in the lubrication gap between the meshing gear teeth flanks can produce pressures greater than 10,000 bar. This results in an increase of viscosity that may be several powers of

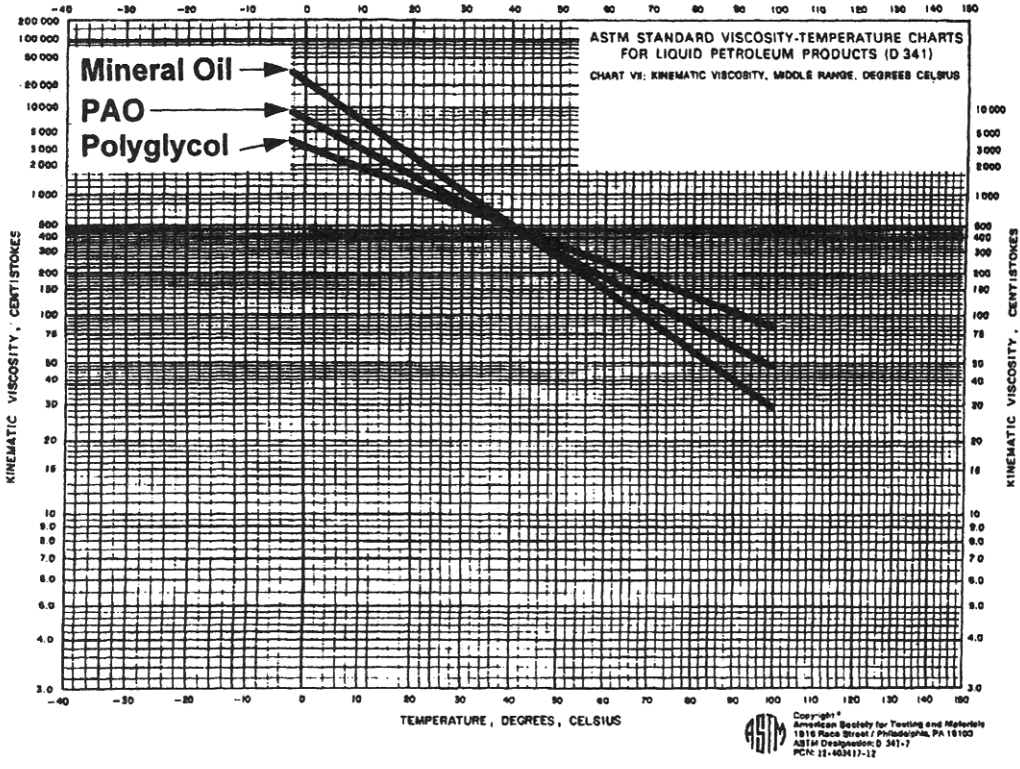

Figure 6 Viscosity-temperature behavior.

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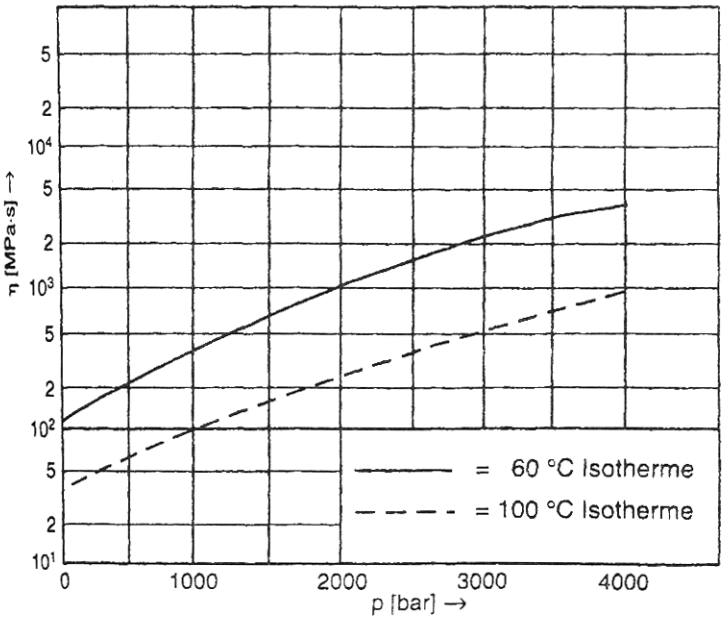

Figure 7 Viscosity-pressure behavior of a synthetic oil ISO VG 220.

10 higher than the initial viscosity of the oil under atmospheric pressure conditions. Figure 7 shows the isothermal increase of absolute viscosity of an ISO viscosity grade 220 synthetic oil at 60 and 100°C as pressure varies from 1 to 4000 bar [2].

B. Oxidation Stability

External impacts continuously change an oil's chemical structure, thus causing it to oxidize or age. Changes occur mainly when the oil is subject to high temperatures, when the oil mixes with air, and when it is in contact with a metal catalyst, such as copper or iron. The speed of the aging process primarily depends on the oil structure and the amount and duration of heat to which the oil is subjected. Additives can be used to retard or stabilize the rate of oxidation. Contaminants such as water, rust, or dust also have a negative impact on oil oxidation. Oxidation is indicated by oil discoloration, increased viscosity, and formation of acids that enhance corrosion, as well as the presence of residues in the form of lacquer, gum, or sludge clogging oil lines and filters. The oils demulsibility and antifoaming tendencies, as well as anticorrosion and antiwear properties, are impacted negatively by oil oxidation. When a mineral oil is used, the permanent bath temperature should never exceed 80°C because the oxidation process doubles in speed with every 10 K temperature increase above this temperature. Synthetic gear oils are much more resistant to oxidation than mineral oils in similar applications. Oil change intervals can be five times longer, or operating temperatures can be allowed to increase significantly at the same change interval, when a synthetic gear oil is used. Figure 8 shows how mineral oils, PAOs, and PAGs differ in change intervals at varying sump temperatures [5].

C. Application Testing

There has been considerable testing to determine the influence of different lubricants on gear system performance. One of the major components of a lubricant that influences the pitting or

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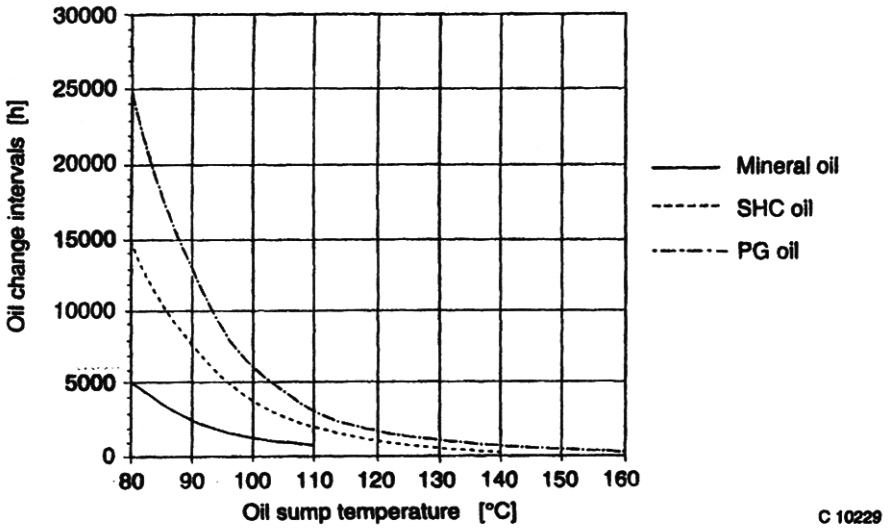

Figure 8 Approximate oil change intervals in gears with oil sump lubrication.

micropitting resistance of gears is the coefficient of friction [6]. Studies show that if the coefficient of friction could be cut in half, the micropitting load capacity could be increased by 1.7 times. This testing was performed on the FZG gear test rig. Using the same test rig, the Institute for Vehicle Engineering and Gear Design of the Technical University of Munich determined that the coefficients of friction for a PAO and a PAG gear oil are significantly less than the coefficient of friction of a mineral oil of similar viscosity (Table 8).

Further testing for the total power loss of gears using the FZG gear test rig shows that not only the viscosity of the gear lubricant but its type has a significant influence [7]. This study determined that the churning losses in a gearbox depend mainly on the viscosity of the lubricant, not the lubricant type. As was shown earlier in connection with the viscosity–temperature behavior of synthetic gear lubricants, it is possible to have a lower viscosity lubricant at start-up in a gearbox and still maintain the same viscosity at operating temperature, thus reducing churning losses. On the other hand, mesh power losses in the gear train depended mainly on the type of lubricant, not the viscosity–temperature relationship or oil additives. Mesh power loss can be reduced by as much as 50% of the power loss of mineral oils by using PAG lubricants. Figure 9, which summarizes the results of the investigation, shows that PAO gear oils have a mean value of 80% and PAG gear oils have a mean value of 70% of the coefficient of friction for mineral oils.

Table 8 Comparison of Coefficients of Friction

Product	ISO viscosity grade	Mean gear friction coefficient μ_{mz}
Mineral oil base EP gear oil	220	0.048
Synthetic gear oil, PAO base	220	0.036
Synthetic gear oil, polyglycol base	220	0.033

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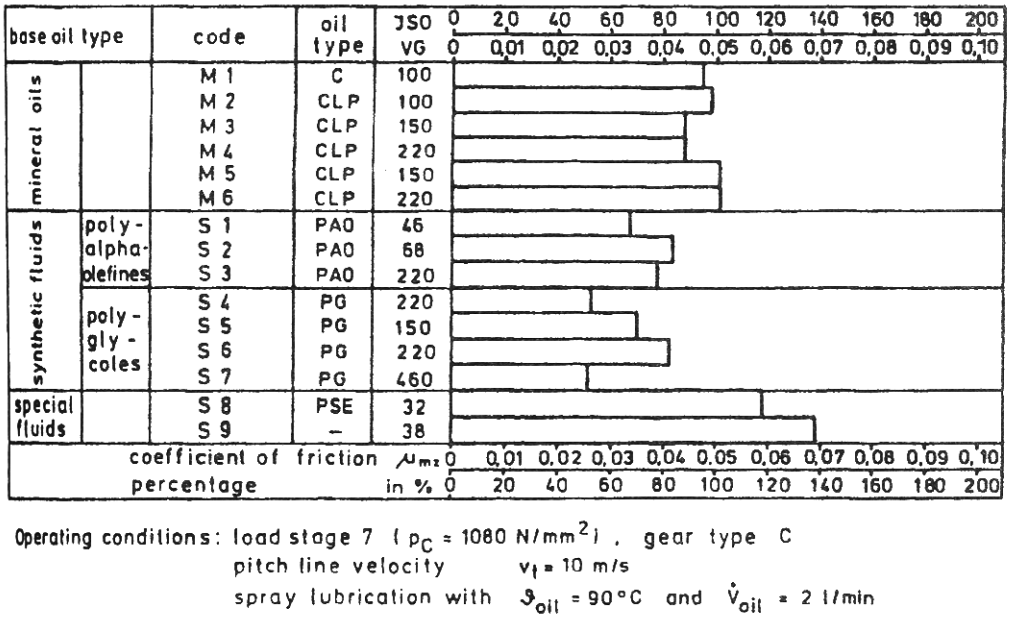
base oil type
code
oil type
ISO VG
mineral oils
synthetic fluids
poly-alpha-olefines
poly-gly-coles
special fluids
M 1 C 100
M 2 CLP 100
M 3 CLP 150
M 4 CLP 220
M 5 CLP 150
M 6 CLP 220
S 1 PAO 46
S 2 PAO 68
S 3 PAO 220
S 4 PG 220
S 5 PG 150
S 6 PG 220
S 7 PG 460
S 8 PSE 32
S 9 – 38
coefficient of friction μ_{mz} 0 0,01 0,02 0,03 0,04 0,05 0,06 0,07 0,08 0,09 0,10
percentage in % 0 20 40 60 80 100 120 140 160 180 200
Operating conditions: load stage 7 (p_C = 1080 N/mm²) , gear type C
pitch line velocity v_t = 10 m/s
spray lubrication with ϑ_{oil} = 90°C and $\dot{V}_{oil}$ = 2 l/min

Figure 9 Coefficient of friction of different lubricants.

The above research not only has been performed by academia, it has been sponsored and even endorsed by OEM gear box manufactures. A product information sheet from SEW Eurodrive [8] states that tests conducted with PAG oils have shown a higher possible power rating than those in which the standard mineral-based oils were used. At high reduction ratios for worm gear drives, PAG oils offer a 20% increase in output power versus mineral oils. The same performance increase is not possible with synthesized hydrocarbon synthetic oils (PAOs).

Obviously with lower coefficient of friction and less energy consumed, temperatures should be reduced when synthetic gear lubricants are used. In a test it was determined that at 60% of rated power, a PAG gear oil operated approximately 10°C cooler than mineral oil in the worm drive gearbox. Also at 100% rated power the PAG gear lubricant operated at the same temperature as mineral oil when the gearbox was at 70% rated power (Fig. 10) [4].

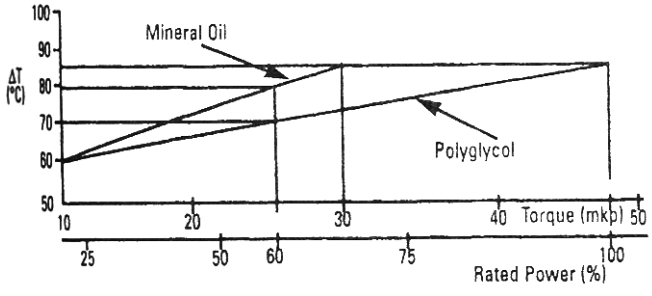

Figure 10 Comparison of polyglycol versus mineral oil in a warm drive gearbox.

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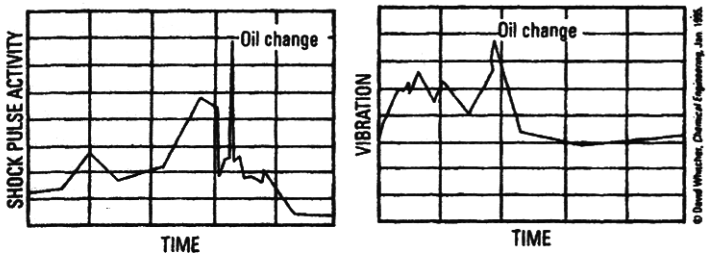

Figure 11 Switching to a synthetic oil immediately reduces shock pulse activity and vibration.

The significant influence of synthetic gear lubricants has also been seen in actual field applications. A Texas power generator who switched to a synthetic oil found that casing temperatures for large speed reducing gears and coal pulverizer gears dropped well in excess of 20°F [9]. Additionally, wear rates were cut to a level that is estimated to double or triple the life of the high torque worm speed reducers and at the same time increase the oil change period fourfold.

Another field experience documented by Willamette Industries showed that an external washer filter in a pulp mill had been operating well above 1.5 G shock pulse activity and 0.2 in./s vibration [9]. After a switch to a synthetic oil, the shock pulse activity dropped to 0.75 G and the vibration reduced to 0.15 in./s. This change occurred immediately and continued for a month (Fig. 11).

The foregoing benefits of synthetic gear lubricants that have been documented for enclosed gearboxes can also be experienced with gear greases made with synthetic base oils, as well as synthetic adhesive lubricants for open gear drives.

V. CURRENT COMMERCIAL PRACTICE

A. Synthetics in Use

Although there are many different synthetic base oils available to use as gear lubricants, only a few have proven to be cost-effective. For industrial gear lubricants, the primary synthetic base oils are:

poly(α-olefins)
(PAOs) polyalkylene glycols: PAGs
esters

In order of use in North America, it is predominantly PAOs, and then PAGs, with esters used in only a few limited applications where the application parameters require the special performance characteristics of the ester oil. In the European Community and other parts of the world there is much larger use of PAGs as industrial gear oils. PAOs are used less and, again, esters have limited use.

Almost all lubricant suppliers today will have available at least a few synthetic gear oils, and a few suppliers offer a significantly broad range of synthetic gear oils. The easiest way to

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locate suppliers in North America is through the use of the Thomas Register. In addition, several trade magazines publish lists of synthetic lubricants available to their industry. Table 9 is an excerpt from *Plant Engineering Magazine*, which publishes a biannual synthetic lubricant buyer's guide [10]. In addition to this list, all international lubricant suppliers have synthetic gear oils.

B. Market for Synthetic Gear Lubricants

The major growth markets for synthetic industrial gear lubricants are the mining, chemical, and food industries. It appears that the driving force for the food processing industry is increased enforcement of the requirements for USDA HI food-grade lubricants. The synthetic HI food-grade lubricants for gear applications can far outperform the nonsynthetic versions. In the mining and chemical fields, as well as in the industrial machine and equipment manufacturing industry, maintenance departments are looking for greater savings through higher performing lubricants, as well as lubricants with longer life. The concept of total cost is slowly overcoming resistance to the high initial price. Also, environmental controls are forcing companies to use chemical management programs that are looking not only at operating costs, but at disposal costs of lubricants. Again, the advantages of synthetic gear lubricants become more evident under these circumstances [11].

C. Industry Demands Higher Performance

Needless to say, all industries, especially in North America, are highly competitive, and to survive in the marketplace each one must maximize its productivity. The easiest route to maximum productivity in a manufacturing operation is to reduce downtime and at the same time increase production. One way to reduce downtime for machinery is to increase gearbox drain intervals or use gearbox lubricants that are filled for life. Synthetic gear lubricants, with their oxidation stability, can fulfill this need. Another way to increase productivity is to increase the speed of the process. This approach usually requires additional heat in the process or generates more heat in the gearboxes. Again, the thermal stability and the viscosity–temperature characteristics of synthetic gear lubricants allow the manufacturer to push the process beyond its current limits without seriously affecting the equipment.

Along with productivity comes efficiency. A manufacturer who can reduce operating costs can be more competitive. Synthetic lubricants provide a lower coefficient of friction in most gearboxes, therefore reducing the energy required to manufacture the part. Also, since the synthetic gear lubricants last longer, fewer maintenance hours are needed to change oil, consequentially freeing up those man-hours to implement other productivity improvements.

Gearbox manufacturers, OEMs, and end users are beginning to demand better gear lubricants to meet tougher performance targets in the following areas [3]:

better thermal stability
longer or no drain intervals (fill for life)
heavier loads
higher quality
more efficiency
extended warranty

Synthetic gear lubricants will play an increased roll in meeting the targets of the future.

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Table 9 A Trade Publication's Chart of Synthetic Lubricants

ISO Viscosity Grade	Viscosity, SUS at 100 F	Kent Oil	Keystone Lubricants	Kluber Lubrication North America	Leahy-Wolf	Lockrey	Lubrication Engineers
Gear & Bearing Circulation Oil							
32	135–165	NRG 32 (1)	213 (3)	Syntheso D 32 (5), Kluberoil 4 UH 1–32 (1)	Syn Master 32 (5)		9032 Syn Air Comp Oil (1)
46	194–236	NRG 46		Syntheso D 46 (5), Kluberoil 4 UH 1-46 (1)	Syn Master 46		
68	284–346	NRG 68		Syntheso D 68 (5), Kluberoil 4 UH 1–68 (1)	Syn Master 68		9068 Syn Air Comp Oil
100	420–520	NRG 100		Syntheso D 100 (5), Kluberoil 4 UH 1–100 (1)	Syn Master 100		9100 Syn Air Comp Oil
150	630–770	NRG 150	215	Syntheso D 150 (5), Kluberoil 4 UH 1–150 (1)	Syn Master 150		9150 Syn Air Comp Oil
220	900–1100	NRG 220	550	Syntheso D 220 (5), Kluberoil 4 UH 1–220 (1)	Syn Master 220		
320	1350–1650	NRG 320		Syntheso D 320 (5)	Syn Master 320		9320 Syn Ind Lube
460	1935–2365	NRG 460		Syntheso D 460 (5), Kluberoil 4 UH 1–460 (1)	Syn Master 460		9460 Syn Ind Lube
Extreme Pressure Gear Oil							
100	420–520	GO 100 (1)		Klubersynth GH 6–100 (5), GEM 4–100 (1)	Syn Master EP 100 (1)		
150	630–770	GO 150	365 (3)	Klubersynth GH 6–150 (5), GEM 4–150 (1)	Syn Master EP 150		
220	900–1100	GO 220	366	Klubersynth GH 6–220 (5), GEM 4–220 (1)	Syn Master EP 220		
320	1350–1650	GO 320		Klubersynth GH 6–320 (5), GEM 4–320 (1)	Syn Master EP 320		9320 Syn Ind Lube (1)
460	1935–2365	GO 460	367	Klubersynth GH 6–460 (5), GEM 4–460 (1)	Syn Master EP 460		9460 Syn Ind Lube

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High Pressure (Antiwear) Hydraulic Oil							
32	135–165	AW 32 (1)		Kluberoil 4 UH 1–32 (1)	Hydrol Syn Master 32 (1)		
46	194–236	AW 46		Kluberoil 4 UH 1–46 (1)	Hydrol Syn Master 46		
68	284–346	AW 68		Kluberoil 4 UH 1–68 (1)	Hydrol Syn Master 68		
100	420–520	AW 100		Kluberoil 4 UH 1–100 (1)	Hydrol Syn Master 100		
Fire Resistant Hydraulic Fluid							
Synthetic		FR (4)					9455 Syn F-R Hyd Fluid (4)
Water Glycol							
Compressor Lubricant							
32	135–170	SCO 32 (1)	214 (Rotary) (3)	Kluberoil 4 UH 1–32 (1)	Lubemaster DL 10 (3)		9032 Syn Air Comp Oil (1)
46	194–236	SCO 46	800 (Rotary) (1)	Kluberoil 4 UH 1–46 (1)			
68	284–355	SCO 68	220 (Rotary) (3)	Kluberoil 4 UH 1–68 (1)	Lubemaster DL 20		9068 Syn Air Comp Oil
100	420–520	SCO 100	219 (Recip) (3)	Kluberoil 4 UH 1–100 (1)	Lubemaster DL 30		9100 Syn Air Comp Oil
150	630–770	SCO 150	222 (Recip) (3)	Kluberoil 4 UH 1–150 (1)	Lubemaster DL 40		9150 Syn Air Comp Oil
Multipurpose Extreme Pressure Grease (without moly)							
150/220	NLGI 2	EP 2 (1)	Performance	Petamo GY 193 (4), GHY 441/3 (4)			
Multipurpose Molybdenium Disulfide Extreme Pressure Grease							
150/220	NLGI 2	MEP 2 (1)				Liqui-Moly NV (5)	
Multipurpose High Temperature Grease (without moly)							
150	NLGI 2	HT 2 (5)		Asonic HQ 72–102 (4), Petamo GY 193 (4)			

(1) Polyalphaolefin (2) Dialkylated Benzene (3) Dibasic Acid Ester (4) Polyol Ester (5) Polyglycol (6) Phosphate Ester (7) Silicone Fluid
Source: Plant Engineering Magazine, p. 76, December, 1994.

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REFERENCES

1. Texaco, Inc., *Lubrication, 6b* (1), (1980).
2. Kluber Lubrication, *Die Schmierung von Zahncadgetrieben,* 3rd ed., Kluber, Munich, 1995, pp. 9.3–9.4.
3. Korosec, P. S., in *Gear Oils, Synthetic Lubricants, and High Performance Functional Fluids,* 1st ed., p. 365–384.
4. Lauer, D. A., Gear oil classification and specification, *Gear Technol.,* May–June, 1995.
5. Kluber Lubrication, *Transmission Engineering, Selection and Application of Gear Lubricants,* Kluber, Munich, August 1995.
6. Winter, H., and Oster, P., Influence of lubrication on pitting and micro-pitting resistance of gears, *Gear Technol.,* March–April 1990.
7. Michaelis, K., and Höhn, B,-R., Influence of lubricants on power loss of cylindrical gears, STLE preprint 93-AM-4B-1, Society of Tribologists and Lubrication Engineers, Park Ridge, IL, 1993.
8. SEW Eurodrive, Product information publication S-002-1, April 1990.
9. Bloch, H. P., and Williams, J. B., Synthetic lubricants measure up to claims, *Chem. Eng.,* p. 127–130, (January, 1995).
10. *Plant Engineering* staff, *Plant Engineering Magazine's* Exclusive Chart of Synthetic Lubricants, Cahners Publishing, Reed Elsevier, Inc., 1994.
11. Downey, B., Kline and Company, personal communication, February 1997.

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